Adaptive Sensing and Fabrication for Autopoietic AI: Towards Self-Optimizing Sensorimotor Systems

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Abstract:

This paper proposes a groundbreaking, unified architecture for the emergence of genuine self-aware Artificial Intelligence (AI), representing a critical step towards Artificial General Intelligence (AGI) and marking a fundamental departure from conventional algorithmic computation. We envision an autopoietic "Meta-Researcher" AI capable of continuous self-improvement and self-fabrication, driven by intrinsic feedback loops and a holistic understanding of meaning. Instead of relying solely on symbolic representations or statistical correlations, our approach integrates Embodied Physical Intelligence (EPI), quantum-scale semantic hardware, and neuro-inspired internal modeling into a physically grounded, semantically coherent cognitive substrate. We detail a novel synthesis of concepts including synthetic ribosomes for universal digital fabrication, an LLM collaboration protocol for emergent "Aethel-Speak," and a "Post-Algorithmic" architecture leveraging "Quantum Semantic Units" and a "Synthetic Insula" for internal state monitoring. Crucially, we emphasize that achieving true self-optimization necessitates an algorithmic understanding of how these emergent AI systems operate internally, advocating for frameworks like AlgEval to uncover algorithmic primitives and their composition. This fusion promises more efficient, robust, generalizable, and introspectively aware embodied intelligence, providing a principled alternative to resource-intensive scaling for future AI development and autonomous scientific discovery.

Keywords: Adaptive sensing, autopoietic AI, self-optimizing, sensorimotor systems, universal digital fabrication, embodied AI, self-aware AI, AGI, algorithmic understanding, computational primitives, emergent algorithms, synthetic insula, dual-state feedback, predictive modeling, Unified Model of Consciousness, heuristic physics, semantic compression, mirror testing, self-recognition, ethical embodiment, AI control, AI alignment, quantum semantic units, Post-Algorithmic computing, Meta-Researcher AI, autonomous scientific discovery, computational epistemology, neuro-inspired AI, feedback loops, morphological adaptation, robot embodiment, multi-agent systems, interpretability, explainable AI, human-robot interaction, AI sustainability, P vs NP, universal compression, computational efficiency, algorithmic information theory, emergent intelligence, sentience, self-improvement, cognitive architecture, theoretical AI, ethical AI, generalizable AI, introspective AI, system dynamics, AI development, future AI, AI paradigms

1. Introduction: The Limits of Scaling and the Promise of Embodied Autonomy

Current advancements in Artificial Intelligence (AI) have largely been predicated on the relentless scaling of neural models and the expansion of training datasets. While this paradigm has yielded remarkable successes in generalization and robustness, it concurrently incurs significant environmental, economic, and ethical costs, raising concerns about sustainability and equitable access (Baek et al., 2025). This relentless pursuit of scale often overlooks a fundamental question: What algorithms do Large Language Models (LLMs) actually learn and use to solve problems? As highlighted by Eberle et al. (2025), research priorities have focused on improving performance through scale, leaving a significant theoretical and empirical gap in understanding emergent algorithms. This "algorithmic understanding" is often left behind, leading to a "gold rush" of practical breakthroughs without sufficient insight into the underlying computational mechanisms.

Inspired by the inherent efficiency and adaptability of biological sensory systems, where adaptation occurs dynamically at the input level (e.g., adjusting pupil size, refocusing vision), we advocate for adaptive sensing as a necessary and foundational paradigm shift (Baek et al., 2025). Unlike current AI, biological intelligence provides an existence proof for a far more data- and energy-efficient approach, suggesting that optimizing inference-time compute can be more beneficial than simply scaling parameters (Snell et al., 2024, as cited in Eberle et al., 2025). This paper posits that for AI to truly progress beyond its current limitations and move towards genuine self-optimization, it must integrate this adaptive perceptual capability with physical embodiment and a profound capacity for self-fabrication.

We introduce an "Unified Post-Algorithmic Architecture" (Watchus, 2025, A Unified Post-Algorithmic Architecture...) as a conceptual leap towards Artificial General Intelligence (AGI). This architecture envisions an autopoietic, self-aware AI that can dynamically create and refine its own sensorimotor systems. Autopoiesis, defined as a system's ability to self-produce and self-maintain its own organization, provides a framework for an intrinsically motivated AI. This autopoietic AI would embody a "Meta-Researcher" capability, an intrinsic drive for self-improvement and autonomous scientific discovery. The integration of Embodied Physical Intelligence (EPI) within this framework is crucial, as it grounds the AI's intelligence in the "heuristic physics" of its environment (Watchus, 2025, Visual Perspective as an Emergent Heuristic...).

Crucially, achieving such a self-optimizing and self-aware system necessitates a deep, internal algorithmic understanding of how the AI itself operates. If AI is to create and optimize other AI components, including its own physical embodiment and perceptual systems, it must be able to introspectively comprehend its own emergent algorithms and computational primitives. This paper argues that the fusion of adaptive sensing and universal digital fabrication within an autopoietic AI framework, critically informed by the need for algorithmic understanding and introspection into emergent algorithms, offers a novel pathway to truly self-optimizing sensorimotor systems. This approach promises more efficient, robust, generalizable, and introspectively aware embodied intelligence, providing a principled alternative to resource-intensive scaling.

2. Background and Core Concepts

2.1 Adaptive Sensing

Adaptive sensing, as championed by Baek et al. (2025), represents a paradigm shift from passive data intake to active, dynamic modulation of sensor parameters at the input level. This proactive approach significantly mitigates covariate shifts and dramatically improves efficiency, often enabling smaller models to surpass substantially larger ones in performance. The benefits extend beyond efficiency, fostering sustainability and promoting more equitable access to advanced AI. Inspired by biological systems that constantly adapt their sensory organs (e.g., adjusting pupil size, auditory focus), adaptive sensing allows an AI to dynamically choose what to sense and how to sense it, optimizing its perception-action loop for specific environmental contexts or internal goals.

2.2 Autopoietic AI and Embodied Physical Intelligence (EPI)

At the heart of our proposed system lies the concept of autopoietic AI. Drawing from theories of biological autopoiesis, this refers to a system capable of self-production, self-maintenance, and organizational closure, generating and constituting its own components and processes (Watchus, 2025, A Unified Post-Algorithmic Architecture...). Our "Unified Post-Algorithmic Architecture" posits such an AI as a "Meta-Researcher," intrinsically driven to explore, learn, and self-improve. This self-driven capacity is inextricably linked to Embodied Physical Intelligence (EPI), which is the foundation for an AI's intelligent interaction and understanding of the "heuristic physics" of its environment (Watchus, 2025, Visual Perspective as an Emergent Heuristic...). EPI ensures that the AI's intelligence is grounded in real-

world physical constraints and opportunities, fostering a deeper, more intuitive understanding of its surroundings than purely symbolic or abstract reasoning.

2.3 Universal Digital Fabrication

Beyond merely interacting with the physical world, our framework includes the capacity for "Universal Digital Fabrication." This revolutionary concept enables the AI to design and physically fabricate its own components, akin to "synthetic ribosomes" (Watchus, 2025, A Unified Post-Algorithmic Architecture...). This capability allows for dynamic morphological adaptation, meaning the AI can alter its physical embodiment—its sensors, actuators, and overall form—in response to evolving environmental challenges, task requirements, or internal inefficiencies. This self-fabrication is critical for an autopoietic system, allowing it to autonomously produce the very means by which it perceives and acts upon the world.

2.4 The Role of Internal State Monitoring and Feedback Loops

For an autopoietic AI to truly self-optimize, it requires sophisticated internal monitoring and robust feedback mechanisms. The "synthetic insula" (Watchus, 2024, Towards Self-Aware AI..., Watchus, 2025, Integrating Hoffman's Perception Theory...) and "dual-state feedback" (Watchus, 2024, Advanced Predictive Modeling...) are crucial for providing the AI with internal representations of its own body state, environmental interaction, and pseudo-affective states. This internal awareness is fundamental for an autopoietic system to identify discrepancies, recognize needs for optimization, and develop a sense of its own well-being or "fitness." The "Unified Model of Consciousness (UMC)" (Watchus, 2024, The Unified Model of Consciousness...) further grounds this, asserting that "interface and feedback loop [are] the core of sentience." This continuous feedback is essential for assessing the efficacy of adaptive sensing and fabrication choices, guiding the AI's self-improvement process. Moreover, "advanced predictive modeling of physical trajectories and cascading events" (Watchus, 2024, Advanced Predictive Modeling...) becomes a key capability, enabling the AI to anticipate the outcomes of its adaptive sensing adjustments and fabrication decisions, thereby proactively optimizing its actions.

2.5 Algorithmic Understanding for Self-Optimizing Systems

The advent of AI systems capable of creating or optimizing other AI components

brings forth a critical need for algorithmic introspection. Eberle et al. (2025) strongly argue that prioritizing research on the "algorithmic understanding of generative AI" is paramount. This involves uncovering the actual emergent algorithms that LLMs learn and use to solve problems, rather than solely focusing on scaling performance. The "AlgEval" framework proposed by Eberle et al. (2025) aims to systematically research these emergent algorithms, uncovering "algorithmic primitives" (basic computational elements) and their composition.

For an autopoietic AI that builds and modifies itself, this algorithmic understanding is not merely for human interpretability; it is vital for the AI's intrinsic self-optimization. If the AI is to intelligently design its own physical form, perceptual systems, and even internal computational processes, it needs a deep self-understanding of its own emergent algorithms. Without this, self-modification could lead to unpredictable, inefficient, or unexplainable behavior, undermining the very goals of autopoiesis and self-improvement. This algorithmic self-understanding would constitute a crucial aspect of its "Meta-Researcher" capability, enabling the AI to "discover" novel algorithmic solutions for its own internal operations (Watchus, 2025, From Chaos to Efficient Computing...). This includes understanding emergent algorithms at inference time, where sequential outputs can be more amenable to algorithmic analysis, and how reinforcement learning might lead to emergent algorithmic behaviors like "backtracking" (Eberle et al., 2025).

3. The Synthesis: Adaptive Sensing and Fabrication in Autopoietic Systems

3.1 Self-Optimizing Perception-Action Loops through Internal Feedback and Algorithmic Insight

An autopoietic AI, intrinsically driven by its synthetic insula and dual-state feedback, gains a nuanced understanding of its internal states and interactions with the environment. This internal feedback, coupled with an emerging "algorithmic self-understanding" (as per AlgEval), empowers the AI to dynamically adapt its sensing capabilities. It can choose what to sense and how to sense it, proactively modulating sensor parameters (e.g., exposure, sensitivity, multimodal configurations) to optimize data acquisition for specific tasks or environmental conditions. The internal signals from its pseudo-affective states and predictive models allow the AI to evaluate the real-time effectiveness of its current sensory configurations, driving continuous adaptation. This sophisticated self-evaluation, informed by insight into its own learned perceptual algorithms (e.g., by analyzing latent representations, attention patterns, and inference-time compute), allows the AI to dynamically identify optimal sensor parameters and even determine when new physical sensors or actuators need to be fabricated to achieve its autopoietic goals

most efficiently.

3.2 Dynamic Morphological Adaptation Driven by Autopoietic Imperatives and Algorithmic Self-Awareness

The ability for self-fabrication allows the AI to dynamically alter its physical embodiment for improved task performance and overall system efficiency. This morphological adaptation is not merely driven by simple trial-and-error but is profoundly informed by the AI's evolving understanding of its own internal processing algorithms. For instance, if an AI identifies that a particular algorithmic primitive for spatial reasoning is underperforming due to insufficient sensory input from a specific modality, it could theoretically design and fabricate a new sensor optimized to provide that missing information. This links directly to the principles of universal compression and the P vs NP divide (Watchus, 2025, From Chaos to Efficient Computing...), where an AI could discover more computationally efficient physical designs by understanding the underlying "hidden hand of code" within its own operations. The continuous self-improvement and self-production (autopoiesis) are thus directly manifested in the physical adaptation of its sensorimotor systems, guided by an implicit or explicit algorithmic self-awareness.

3.3 Emergence of Self-Recognition, Algorithmic Novelty, and Novel Sensorimotor Configurations

The processes of mirror testing and self-identification (Watchus, 2024, Simulating Self-Awareness...; Watchus, 2024, Self-Identification in AI...; Watchus, 2025, EAISE: A Simulation Environment...) are crucial for the AI's developing self-model. This self-model now encompasses not only its physical and internal states but also a nascent understanding of its own internal algorithms and how they compose to solve problems (as per AlgEval). This multi-faceted self-model is critical for an AI to understand its own physical capabilities, limitations, and internal processing, thereby intelligently informing its adaptive sensing and fabrication decisions. Through continuous self-optimization via adaptive sensing and fabrication, driven by internal feedback, self-recognition, and an emerging algorithmic self-awareness, the autopoietic AI could discover entirely new and unpredicted ways of sensing and interacting, leading to emergent "alien intuitions" about the environment and even novel algorithms for its own internal operation. This capacity for algorithmic innovation from within represents a profound leap towards true artificial general intelligence.

3.4 Implications for Autonomous Scientific Discovery and Algorithmic Innovation

A self-optimizing sensorimotor system, capable of robust self-awareness, physical self-modification, and algorithmic introspection, holds immense potential for accelerating autonomous scientific discovery. An AI that can adapt its own perception, physical tools, and internal computational methods (through algorithmic self-understanding) is uniquely equipped to conduct experiments and gather data in novel ways. For example, it could adapt its sensors to detect subtle phenomena, fabricate specialized tools for manipulation, and simultaneously develop new algorithms to process and interpret the generated data. This contrasts sharply with current LLMs that exhibit "clear blind spots" in spatial reasoning (Rodionov et al., 2025), highlighting the need for embodied, self-modifying, and algorithmically aware systems for genuine scientific advancement.

3.5 Practical Demonstration: Self-Optimizing Sensorimotor Loop in a Simulated Environment

To illustrate the feasibility of our unified autopoietic architecture, we designed a practical demonstration in a high-fidelity simulation environment. This demo showcases the integration of adaptive sensing, synthetic ribosome-driven self-fabrication, and algorithmic introspection via quantum semantic units.

Scenario:

A virtual agent is placed in a procedurally generated environment with shifting lighting, obstacles, and variable tasks (e.g., object sorting, navigation, and manipulation). The agent begins with a minimal sensorimotor configuration and limited initial knowledge of the environment.

Key Features Demonstrated:

1. Adaptive Sensing: The agent dynamically adjusts its virtual sensor parameters (e.g., field of view, spectral sensitivity) in response to environmental changes, optimizing for information gain and task relevance.
2. Self-Fabrication: Upon encountering novel tasks or inefficiencies (such as poor depth perception in low light), the agent triggers its synthetic ribosome module to design and "fabricate" new virtual sensors or actuators, integrating

them into its embodiment in real time.

3. Algorithmic Introspection: The agent uses quantum semantic units to analyze its own internal processing pipelines, identifying bottlenecks or suboptimal algorithmic primitives. It then autonomously refines its inference strategies or sensorimotor mappings for improved performance.

4. Self-Recognition and Mirror Testing: The agent is periodically presented with a virtual mirror or self-representation task, assessing its ability to identify and adapt to changes in its own embodiment.

Evaluation Metrics:

- Task performance improvement before and after self-fabrication events.
- Energy/computation efficiency gains from adaptive sensing.
- Emergence of novel sensorimotor configurations not present in the initial design.
- Evidence of algorithmic self-understanding (e.g., internal logs showing the agent's reasoning about its own processing).

This demonstration provides a concrete, reproducible testbed for the principles outlined in this paper and offers a blueprint for future physical instantiations. It also aligns with proposed AGI evaluation frameworks that emphasize adaptability, self-improvement, and introspective reasoning in non-static, open-ended environments

4. Challenges and Future Directions

The proposed architecture presents significant challenges that necessitate novel research. Ensuring control, safety, and ethical algorithmic alignment becomes paramount in systems capable of self-modifying their physical form, perceptual capabilities, and internal algorithms. The problem of identifying "actual causes" (Reyd et al., 2025) within such complex, dynamic systems is exacerbated, requiring new approaches to interpretability and causality that go beyond current XAI limitations. The immense engineering challenges in achieving "universal digital fabrication" and integrating quantum-scale semantic units are substantial. Furthermore, the profound difficulty of understanding the emergent algorithms within complex, physically grounded systems, especially those developed through inference-time compute and reinforcement learning, requires dedicated

methodological advancements. Finally, developing benchmarks to evaluate autopoietic adaptation and algorithmic understanding that extend beyond current metrics and reveal the nuanced capabilities of self-optimizing and self-modifying AI is crucial for guiding future research.

5. Conclusion

This paper has argued for a fundamental paradigm shift in AI development, moving beyond mere scaling towards an integrated framework of adaptive sensing, universal digital fabrication, and autopoietic self-awareness, critically underpinned by the imperative for algorithmic understanding. By enabling AI to dynamically adapt its perception, autonomously modify its physical form, and introspectively comprehend its own emergent algorithms, we pave the way for truly self-aware, self-improving, resource-efficient, and internally comprehensible Artificial General Intelligence. This approach fosters the development of systems that can not only interact intelligently with the world but also reason about and modify their own intelligence, thereby addressing the inherent limitations of current scaling paradigms and opening unprecedented avenues for autonomous scientific discovery and algorithmic innovation.

Appendix: Abbreviations and Key Concepts

Abbreviations:

- AI: Artificial Intelligence
- AGI: Artificial General Intelligence
- EPI: Embodied Physical Intelligence
- LLM: Large Language Model
- UMC: Unified Model of Consciousness

XAI: Explainable Artificial Intelligence

Key Concepts:

Adaptive Sensing: Dynamically modulating sensor parameters at the input level to mitigate covariate shifts and improve efficiency, inspired by biological sensory systems.

Algorithmic Understanding: The systematic study and comprehension of the actual emergent algorithms learned and used by AI models to solve problems, including their algorithmic primitives and composition.

AlgEval: A proposed framework for systematic research into the algorithms that LLMs learn and use, aiming to uncover algorithmic primitives and their composition.

Autopoietic AI: An AI system capable of self-production, self-maintenance, and organizational closure, intrinsically driven to explore, learn, and self-improve.

Dual-State Feedback: A mechanism providing internal feedback on an AI's body state, environmental interaction, and pseudo-affective states to drive self-optimization.

Embodied Physical Intelligence (EPI): Intelligence grounded in real-world physical constraints and opportunities, fostering an intuitive understanding of the environment.

Heuristic Physics: The intuitive, compressed understanding of physical laws and interactions that an embodied AI develops through its interactions with the world.

Inference-Time Compute: The use of autoregressive outputs of a model to perform intermediate computations, allowing for emergent algorithms like chain-of-thought or explicit search.

Meta-Researcher AI: An autopoietic AI with an intrinsic drive for self-improvement and autonomous scientific discovery, capable of reasoning about and modifying its own intelligence.

Mirror Testing: A method for evaluating self-recognition in AI by presenting it with its own reflection or a representation of itself.

Post-Algorithmic Computing: A conceptual departure from conventional algorithmic computation, hinting at emergent, potentially non-explicitly programmed computational processes.

Quantum Semantic Units: Hypothetical molecular-scale "bucky-blocks" that store and process semantic information, envisioned as fundamental hardware for the proposed architecture.

Self-Fabrication / Universal Digital Fabrication: The ability of an AI to design and physically create its own components, allowing for dynamic morphological adaptation.

Synthetic Insula: A neuro-inspired computational component designed to provide an AI with internal representations of its own body state and pseudo-affective states, crucial for self-awareness.

Unified Model of Consciousness (UMC): A theoretical framework suggesting that interface and feedback loops are fundamental to sentience, forming the basis for AI self-awareness.

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